# Effects of Multiple Scattering on the Implementation of an Underwater Wireless Optical Communications Link

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**Abstract-Recent interest in ocean exploration has brought about a desire for developing wireless communication techniques in this challenging environment. Due to its high attenuation in water, a radio frequency (RF) carrier is not the optimum choice. Acoustic techniques have made tremendous progress in establishing wireless underwater links, but they are ultimately limited in bandwidth. A third option is optical radiation, which is discussed in this paper. One drawback of underwater wireless optical communications is that the transmission of the optical carrier is highly dependent on water type. This study examines some of the challenges in implementing an optical link in turbid water environments and attempts to answer how water clarity affects the overall link.**

## I. INTRODUCTION

Now more than ever, wireless radio frequency (RF) communications are an essential part of military and civilian activities. Land-to-land and land-to-air systems are vital for transmitting data over large distances without the need for a cable connection. Underwater vehicles and devices may also benefit from a wireless link. Military platforms like submarines and unmanned underwater vehicles (UUV's) would gain the ability to coordinate missions and pass data between platforms while at speed and depth. Commercial oceanographic applications stand to profit as well. Data logging sensors such as seismometers or temperature sensing devices obtain the capability to transmit their data without the need to be recovered or unmoored. It is well known however, that while radio frequencies have enjoyed relatively large success in free space, they experience high attenuation in water, and are typically not used for communication between subsurface vehicles and devices.

Acoustic radiation has managed to overcome this issue to some extent. Typically, data rates of >100kHz have been reported for links <100m and data rates <10kHz for links 1km and beyond [1,2,3]. In water, the attenuation of the acoustic carrier with increasing frequency and the effects of multipath reflections will ultimately limit the bandwidth capacity for such systems.

Optical radiation is yet another alternative for creating wireless underwater links. Wireless optical links are becoming more common in atmospheric scenarios, and are showing promise of supporting large bandwidths [4]. Implementing optical links in underwater scenarios however has its own shortcomings since the quality of the optical carrier is highly dependent on the water clarity in a given environment. While the optical properties of water have been studied for some time now, very rarely are they considered from the standpoint of implementing a laser communications link. Prior feasibility studies of underwater wireless optical communications done in decades past have been incomplete in that they were performed in clean water or the transmitter power was varied to simulate attenuation due to the environment [5,6]. As such, the true effect of water turbidity on link range, data rate, and pointing accuracy is still unknown. This experimental work attempts to fill this void.

## II. SYSTEM IMPLEMENTATION

The underwater optical communications system (UWOC) in this study was developed entirely from the same hardware that is used in the Frequency Agile Modulated Imaging System (FAMIS). The FAMIS system is an underwater laser imaging system also being developed at the Naval Air Warfare Center at Patuxent River [7,8]. Detection and imaging in the underwater environment is a challenging task. As previously mentioned, because radio frequencies undergo large amounts of attenuation in water, traditional RF and radar systems are not an optimum choice for this task. However optical systems employing either continuous wave (CW) [9,10] or pulsed/ranged gated [11] techniques are gaining popularity for use in underwater scenarios. FAMIS is a novel system that attempts to marry the transmission characteristics of optical energy, with the well-established signal processing techniques of RF and radar systems.

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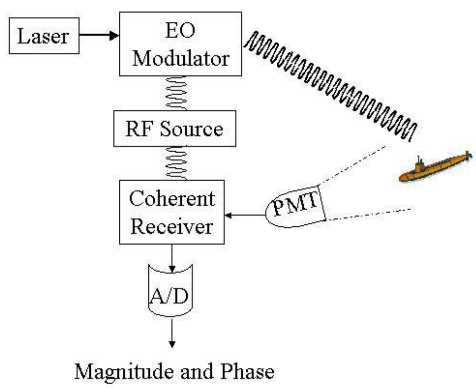



Fig. 1. Block diagram of the FAMIS imaging system. A CW laser is amplitude modulated by an RF source. Once recovered, radar techniques provide magnitude and phase information of the image.

A block diagram of this system is shown in figure 1. In this system, a continuous wave (CW) laser is modulated at radio frequencies between 10-100MHz by an electro-optic modulator. The return signal from the target is detected with a photomultiplier tube and demodulated by a coherent receiver. Magnitude and phase information of the target of interest is then determined. One major benefit of the FAMIS approach is that it leverages off of well-established signal processing techniques and hardware from the radar community. The main difference is that the carrier is in the form of optical energy, rather than radio waves.

Radar and communication systems are characteristically similar systems. The foundation of many of the digital modulation schemes used in terrestrial links are related to basic radar detection techniques and use similar hardware components. As such, we can use the modulation that FAMIS provides to create an underwater wireless optical communications link.

Specifically in this work, a Phase Shift Keying (PSK) link is examined. In PSK, digital data is represented as changes in a sinusoidal phase. For a *k*-bit system, the number of symbols is $m = 2^k$ where a PSK symbol is defined as

$$S_k = A\cos(wt + \frac{2\pi k}{m}), \quad k=1,\ldots.m \tag{1}$$

For simplicity, a binary phase shift keying (BPSK) link is implemented here (k=1, m=2).

## III. IMPLICATIONS OF ESTABLISHING OPTICAL LINKS IN WATER

The main challenge of implementing an optical link underwater is that the optical signal is highly variable with water optical properties. An optical signal is attenuated in water by two processes, absorption and scattering. The absorption and scattering coefficients, $a(\lambda)$ and $b(\lambda)$ respectively, are wavelength dependent. Absorption losses occur as photon energies are lost due to thermal processes. Scattering losses occur when the interaction with particulates causes photons to scatter out of the main beam path. It is often more convenient to represent these losses together as the total attenuation. The attenuation coefficient, $c(\lambda)$, is defined as,

$$a(\lambda) + b(\lambda) = c(\lambda) \tag{2}$$

For an incident optical source with power, $P_0$, the received power, $P_r$ at some point *d* meters away is,

$$P_r(\lambda, d) = P_0 e^{(a(\lambda)+b(\lambda))d} = P_0 e^{c(\lambda)d} \tag{3}$$

Table 1 shows some representative absorption, scattering, and attenuation coefficients for various water types [12].

When the receiver is viewing the optical signal off-axis (which is a likely operational scenario), the received power is a function of the attenuation coefficient and the volume scattering function, $\beta(\theta)$. The volume scattering function describes the angular dependence of scattered light. The received power is then defined as,

$$P_r(\lambda, d) = P_0 e^{c(\lambda)d} \beta(\theta) \tag{4}$$

The impact of water clarity on an underwater optical communications link should now be apparent, as both absorption and scattering have different effects depending on the environment. For example, in pure sea water, absorption will ultimately be the limiting factor with increasing distance. In this case, we can choose a laser source whose wavelength is optimized so that it experiences a minimum amount of absorption. This ranges from blue to green wavelengths depending on water clarity. Furthermore, the fact that the beam remains relatively collimated over a given path length in clean water imposes extra pointing requirements on the system since the transmitter and receiver would have to be well aligned. It is plausible that beam divergence (whether natural due to range, or imposed via optics) may relax this requirement, however the operational environment (on a submarine or UUV) may prohibit making physical changes on the fly.

On the other hand, in turbid harbor waters, scattering may be the limiting factor. Here, the well-collimated nature of laser light is virtually destroyed as photons begin to scatter out of the main beam path. From a system standpoint, this may be a benefit in that we are able to relax the pointing requirements since the optical signal now starts to approach that of an isotropic source. However, scattering may have a similar adverse effect on optical signals that multipath reflections have on acoustic signals. Several studies have investigated the

TABLE 1

Inherent optical properties of various water types. $\lambda$=514nm

| Water Type | A ($m^{-1}$) | b ($m^{-1}$) | c ($m^{-1}$) |
|---|---|---|---|
| Pure sea water | .0405 | .0025 | .043 |
| Clean ocean | .114 | .037 | .151 |
| Coastal ocean | .179 | .219 | .298 |
| Turbid harbor | .266 | 1.824 | 2.19 |

spreading effects of water clarity on baseband optical pulses [13]. In the case of a modulated carrier, such as the BPSK link examined here, we wish to examine how water clarity, particularly the off-axis scattering of photons, affects the transmitted modulated RF subcarrier.

To this end, we define a modulation depth,

$$m(f) = \frac{P_{RF\max}(f) - P_{RF\min}(f)}{2P_0} \tag{4}$$

where $P_{RF}$ is the incoming modulated component of the optical signal and $P_0$ is the non-modulated, or DC, component. Ideally, the modulation depth is unity. However, depending on transmitter/receiver alignment, link range, RF modulation wavelength, and water turbidity, the possibility exists that loss of modulation could occur. From a communications perspective, loss of modulation depth translates directly into received signal-to-noise loss, and therefore a higher probability of bit error. As such, it is important to understand what role scattering has on the modulated optical signal.

## IV. EXPERIMENTAL SETUP AND PROCEDURE

A block diagram for the laboratory BPSK link is shown in Figure 2. Experiments were conducted in a 1m x 1m x 3.66m water tank with windows on each end. Maalox antacid was used as a scattering agent [14] and a transmissometer was used to directly measure the attenuation coefficient in the testing tank. The transmitter and receiver are located outside the tank on opposite sides. At the transmitter end, a frequency-doubled diode-pumped solid-state laser (532nm) is used as the optical source. While this laser has a maximum adjustable output power of 5W, an output setting of 3W is used in this study. The CW optical signal enters an electro-optic modulator that has a modulation bandwidth of approximately 10-100Mhz. A carrier frequency of 70Mhz was chosen for these experiments. A programmable frequency synthesizer was used to generate the RF carrier signal. This source can be programmed to store the PSK symbols in memory. In the case of the BPSK link implemented here and as defined by (1), two 70Mhz sinusoids 180 degrees apart from each other are stored. After losses through the modulator and other optical elements, the optical power entering the tank is approximately 500mW.

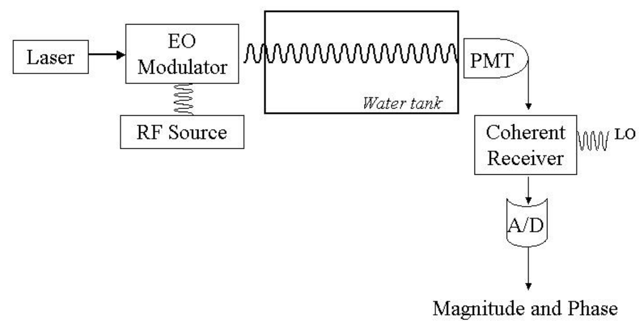



Fig. 2. Simplified block diagram of the laboratory BPSK link.

At the receiver end, a photomultiplier tube was used to recover the RF modulation envelope. A PMT was chosen because of its low noise/high gain characteristics. In addition, the PMT chosen has a 2in. aperture (approximately 18 degrees FOV when housed with biasing electronics). The large active area was chosen in order to collect as much of the scattered light possible.

The signal is then passed through a custom bias-T to separate the RF and DC components. The DC side is lowpass filtered and digitized. The RF is bandpass filtered at 70Mhz and amplified by a 30dB low noise amplifier and a 50dB variable gain amplifier. The carrier is then demodulated via an IQ demodulator. The I and Q samples are lowpass filtered and digitized. Digitization is done with a National Instruments DAQ card which performs simultaneous sampling of the I, Q, and DC signals.

The RF source has two channels. While these two channels can be tuned separately in frequency and phase, they share the same internal oscillator, and are therefore phase-locked. In this laboratory implementation, one channel serves as phase modulation for the transmitter, while the other serves as the local oscillator reference for the demodulator. While having a shared phase locked source between the transmitter and receiver is never likely to happen in a real situation, it does provide a frequency and phase locked signal on both ends of the link. By making the link inherently coherent the experiment can focus solely on the effects of the water channel.

On the receiver end of the tank, the PMT is placed on a motorized rail. Once the transmitter and receiver are aligned, the PMT was moved at 1cm increments off axis. The window of the tank allows for approximately 30 cm of motion, which gives a pointing mismatch of roughly 5 degrees half angle relative to the laser source. At each position, 1ms (5000 samples at 5MS/s) of I and Q data was taken for one of the BPSK phase states. The phase state is changed (180 degrees as per BPSK), and another 1ms of data was taken. The process is essentially equivalent to transmitting a single binary

1 and binary 0 at 1kHz. In post processing, smaller integration times can be examined. In this way, multiple data rates can be examined from one data acquisition measurement. This process is repeated for increasing water turbidities (increasing Maalox concentration).

## V. EXPERIMENTAL RESULTS – PART I

It is often useful to describe the undersea environment in terms of attenuation *lengths*, i.e. the attenuation coefficient multiplied by the physical range at which the system is operating. Figure 3 shows the normalized beam spread vs. position for increasing attenuation lengths (water turbidities). This is simply the DC average of the modulated signal as measured directly from the DC side of the receiver's bias T. Position 0 on the x-axis is the position where the transmitter and receiver are precisely aligned. For the cleanest water types (c = ~0.8/m, cd = ~3), we notice a prominent forward peak that falls off rapidly upon moving off axis, indicating that little scattering is occurring. As water turbidity increases (c = ~24/m, cd = 88) it is easy to notice the influence that multiple scattering has on the optical signal. At the higher water turbidities, the optical signal becomes largely diffuse over the 5-degree measurement range. Furthermore, we observe a slight peak that occurs towards the middle of the acquisition range. Here, photons scattered into the near forward angles are greater than the non-scattered photons. While this provides a clear understanding of the effect of forward scattering on the optical signal, it does not yet answer how the RF part of the signal is influenced.

The following data is shown for an integration time equal to a 100kHz signaling rate. Figure 4 shows modulation depth as defined in equation (4) as a function of position. Here, it appears that even at the highest water turbidities there is no significant loss of modulation with increasing turbidity or pointing mismatch. (The EO modulator typically achieves 90-100% modulation depth with fine alignment). It should be noted however, that increasing the range of the link, increasing the RF subcarrier frequency (decreasing the wavelength), or increasing the pointing inaccuracy beyond 5 degrees, may in fact show that modulation loss can occur. This will be discussed later.

We can also examine the affect of water clarity by examining the phase of the incoming modulated optical signal. As previously mentioned, the link is implemented coherently since the receiver and transmitter signals are derived from the same digital oscillator. The detection, however, is done in a differential sense. In this case, decisions are made not on the absolute phase of the incoming signal but the phase difference between adjacent bit periods. As such, differential detection offers a reduced system complexity. While differential detection of coherent PSK isn't necessarily a common technique, it allows us to observe some interesting phenomena.

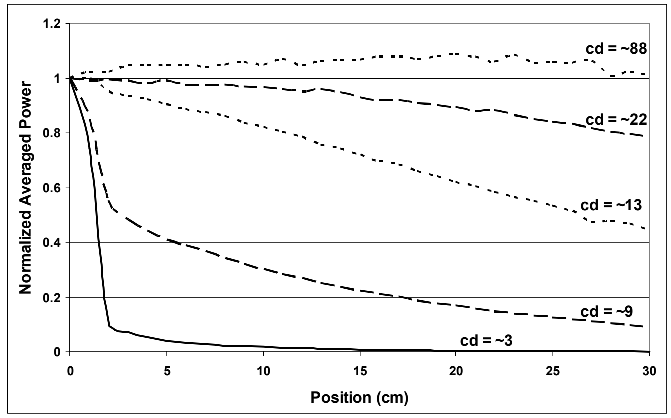



Fig. 3. Normalized beam spread vs. position for increasing water turbidities. For clean waters, the majority of the optical energy is contained in the main beam path. As turbidity increases, photons scatter away from the main beam and into the near forward angles.

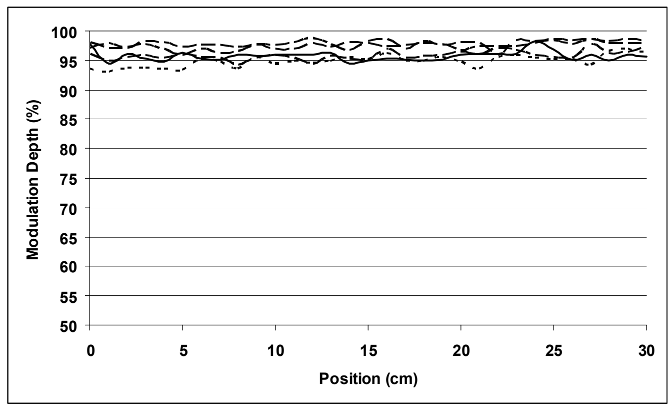



Fig. 4. Modulation depth vs. position for increasing water turbidity. No appreciable modulation depth is lost at the highest water turbidity (c= ~24/m, cd =~90). Integration time is equal to 100kHz signaling rate.

Figure 5 shows the phase difference between binary states versus position for increasing water turbidities. The figure clearly illustrates that even at the highest water turbidities, the phase difference between symbols remains 180 degrees, consistent with BSPK signaling. These are promising results, as it suggests that even in the most challenging underwater environments, the phase modulation is largely unaffected.

As alluded to earlier, an investigation of the absolute phase provides some insight into the effect of scattering on the RF subcarrier. Figure 6 shows absolute received phase vs. position for increasing water turbidity for one of the two BPSK binary states. We notice that from the cleanest water type investigated (c = 0.8 /m, cd = ~3) to the most turbid (c = ~24/m, cd = ~88), the absolute phase shifts approximately 70-80 degrees. This is evidence that multiple scattering is in fact occurring.

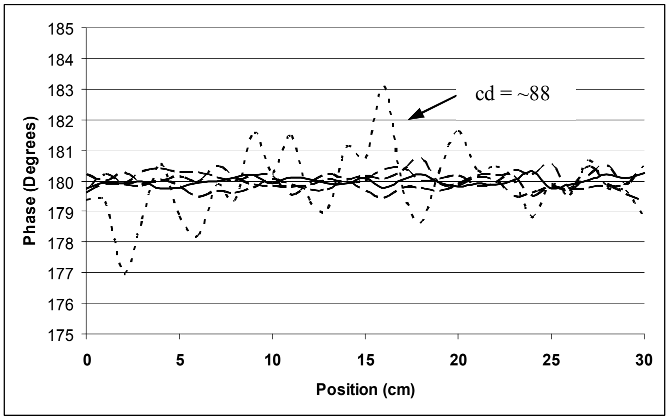



Fig. 5. Phase difference between BPSK states vs. position for increasing water turbidity. Symbols largely remain 180 degrees apart. Even at the highest water turbidity (c=~24, cd=~90), the maximum error is only approximately +/-3 degrees.

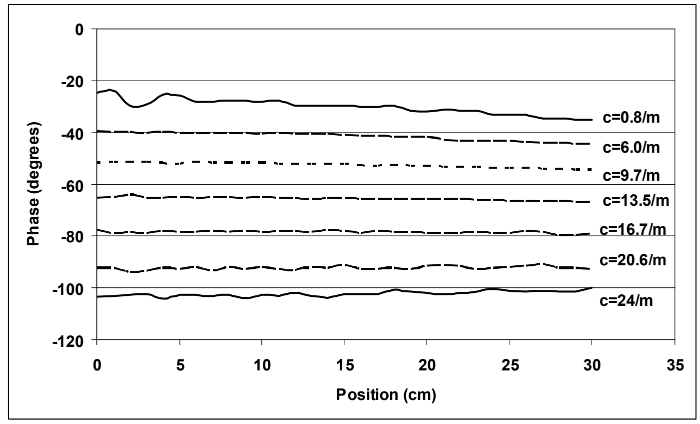



Fig. 6. Absolute phase of one BPSK state vs. position for increasing water turbidity. The modulated optical carrier undergoes a shift of approximately 70-80 degrees (~2ft) due to multiple scattering. Integration time is equal to 100kHz signaling rate

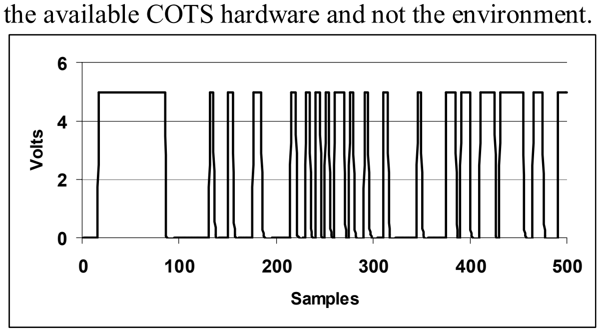
As water turbidity increases, more scattering events occur, and modulated photons take slightly longer path lengths before they reach the receiver. This in turn manifests itself as changes in the absolute phase of the carrier. At 70Mhz, in water, the 70-80 degree shift corresponds to a path length difference of approximately 0.5m-0.7m (~2ft) between the cleanest and dirtiest waters examined here. This distance is certainly plausible over the 3.66m path length given the highly diffuse nature of the light observed at those high turbidities.

## VI. EXPERIMENTAL RESULTS – PART II

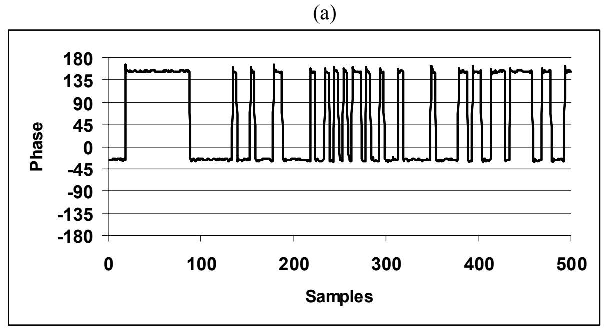
In the previous section, we examined the influence of water clarity on a modulated optical signal. In this section, we describe an experiment to investigate bit error vs. water turbidity and pointing accuracy. Since a bit error generator was not available in the lab, one was made in software via LabView. A pattern generator was used to create a 1024 bit pseudorandom bit sequence (PRBS) at the rate of 1Mbps. The TTL pattern is fed to the RF synthesizer. The card is programmed so that the channel driving the EO modulator changes phases based on the pattern generator sequence. The output of the pattern generator is also digitized by the National Instruments A/D so that comparisons between the transmitted and received message can be performed.

At the other end of the link, the PMT is aligned so that it is off-axis with the transmitted optical signal (5 degrees, as before), giving what should be the "worst-case" scenario in terms of pointing for this particular experimental setup. I and Q samples are then acquired at a sampling rate of 5MHz. Maalox is again added to increase water turbidity. Relatively clean water is examined first (c= 0.35/m, cd= ~1.26). Figure 7a shows approximately the first 80 bits of the TTL signal generated by the pattern generator and figure 7b the corresponding received signal (as changes in phase). Bit decisions were made based on the incoming changes in phase, and the detected sequence was compared to the generated sequence. For this water type, all 1024 bits were detected error free at a data rate of 1Mbps. Figure 8 shows the resultant polar plot. The tight clustering also shows error free transmission.

More turbid waters were examined as well (c = 21/m, cd = ~71). The 1024 bit sequence was again detected error free. The polar plot is shown in figure 9. Both show that the highly scattering environment had little appreciable effect on closing the link. Data rates higher than 1Mbps should be attainable, as the limiting factor in this work was the available COTS hardware and not the environment.




(a)




(b)

Fig. 7. (a)Approximately the first 80 bits of the 1024 bit TTL PRBS and (b) The corresponding received data stream, shown as changes in phase

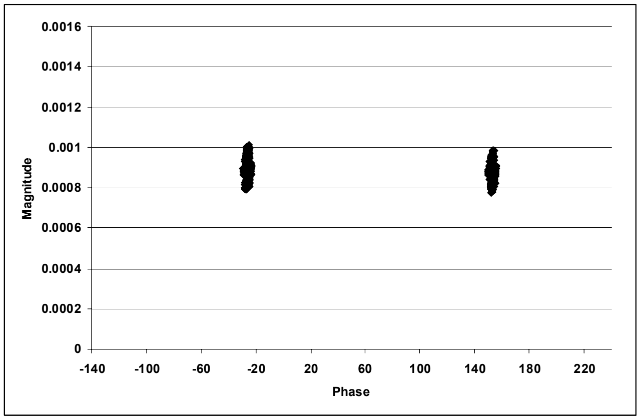



Fig. 8. Polar plot shows error free data. Clean water (c = 0.35/m, cd=1.26). 1024-bit PRBS sequence. 1Mbps.

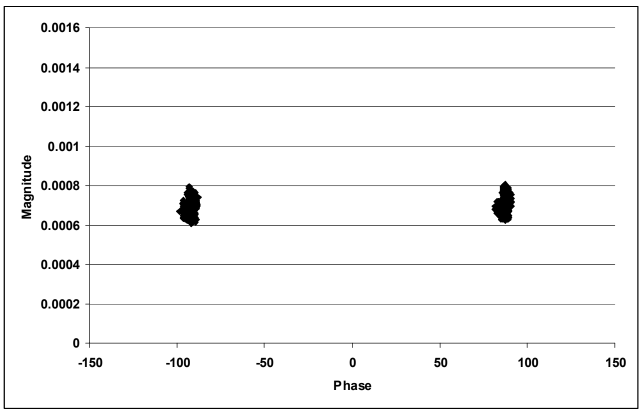



Fig. 9. Polar plot shows error free data. Turbid water (c = 0.35/m, cd=1.26). 1024-bit PRBS sequence at 1Mbps.

## VII. CONCLUSIONS

This work investigated the effects of multiple scattering in turbid environments on a modulated optical signal for establishing wireless underwater communication links. Preliminary experiments showed that recovery of the RF sub-carrier was largely unaffected by water clarity. Changes in the absolute phase of the recovered RF envelope vs. increasing water turbidity confirm that multiple scattering is occurring, however it appears that unlike acoustic systems, the multipath effects are static during the acquisition time. This was supported when short data bursts were detected error free at a rate of 1Mbps.

While these are positive results, it is important to keep in mind a few limiting factors of the experimental setup. First, while extremely high water turbidities were examined, the geometry of the tank provided only for a limited range (3m) and limited pointing inaccuracies (5 degrees). While the link was successfully established at large attenuation lengths (high water turbidities at short ranges), it may be unwise at this point to extrapolate these results to posit on the link quality at long ranges (100m and beyond). It is imperative that pointing accuracy, water clarity, and link range are all considered together.

To further investigate these three factors, additional experiments will be performed in a larger tank facility. The authors at Patuxent River are outfitting an 8m diameter sonobouy tank with windows. This will allow researchers to investigate the effect water turbidity has on longer ranges and wider pointing inaccuracies. As mentioned, the observation that scattering had little effect on the modulated RF sub-carrier may simply be due to the long carrier wavelengths (~3.2m) relative to the short link range (3.66m). Likewise, carrier degradation may occur for pointing mismatches greater than the 5 degrees investigated here. This bigger test geometry should give more insight into the operational limitations of an optical system.

Future plans also include modeling the optical signal in turbid environments. The authors currently possess a beam spread model for investigating the spatial dependence of scattered photons. Such a model will allow researchers to obtain a clearer picture of what kind of pointing accuracies may be necessary for a given water clarity. Future upgrades to this model include the addition of time dependence so that metrics related to the modulated RF sub-carrier may be investigated.

## ACKNOWLEDGMENT

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